JHU–TIPAC 940014
August 1994

Localized Energy Deposition in Neutrino Telescopes: a Signature of "New Physics"

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A class of phenomena either not contained in the Standard Model or in its perturbative treatment (multiple W/Z production, compositeness of quarks and leptons) leads to a large energy deposition in neutrino telescopes within a rather small volume. The shape of the particle distribution arising from such phenomena is estimated.

Neutrino telescopes may play a significant role in particle physics as well as in neutrino astronomy. The basis for their value as particle physics tools lies in the fact that, according to a variety of estimates, *cf.* refs. [1], active galactic nuclei (AGN) as well as other point sources are likely to be sources of ultra high energy (UHE) neutrinos, with energies up to, perhaps, several TeV in the CMS in the interaction with nucleons (energies of the order of a few times 10^7GeV in the laboratory). No currently functioning or planned terrestrial device can compete with such neutrino energies. If the detector is sufficiently large, the limitation due to the low expected flux can be, in part, overcome. Even though the subject of UHE neutrino emission from AGNs and other point sources is at present a controversial one, in a few years, there will be a sufficient amount of data from neutrino telescopes available in order to confirm the existence (or absence) of such neutrinos. What follows is contingent upon the existence of UHE neutrinos emitted by *some* sources.

An obvious advantage of the experimentation with neutrino beams is a relatively low background of "mundane" physics; hence, one expects the study of neutrino induced reactions to serve as a useful tool in looking for phenomena beyond the Standard Model, *cf.* [2].

We propose that if there exists another level of compositeness with a characteristic energy scale of a few TeV, [3, 4], one is likely to discover it in a neutrino telescope by means of a large energy release in a small volume within or near the

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telescope. Likewise, if the conjectured phenomenon of multiple W/Z production (with or without the violation of B+L, see [5]) exists with a comparable cross section [6], one will observe a somewhat similar phenomenon. We conjecture that one will be able to distinguish between the two types of phenomena experimentally; we return to the discussion of this topic later.

The phenomena referred to above are conjectured to have a cross section of the order of a few microbarns, *cf.* [4, 6]. In addition, both processes are characterized by the production of a substantial number ($5 \lesssim \langle N \rangle \lesssim 30$) of energetic hadrons: in the case of composite models of quarks and leptons this was estimated in ref. [4]; in the case of multiple gauge boson production, it is a consequence of the fact that the weak gauge bosons decay into hadron with a branching ratio of about 70%, see [8].

Next, we notice that in a "typical" neutrino telescope, for instance, DUMAND or NESTOR, the detector lies beneath about 4 km. of water, corresponding to a thickness, $d \approx 4 \times 10^5 \mathrm{g/cm}^2$ at zero zenith angle. At a non–vanishing zenith angle, ζ, the absorber thickness is given to a good approximation by the elementary formula:

$$t(\zeta) \approx R\left(\sqrt{(\cos\zeta)^2 + 2d/R} - \cos\zeta\right), \tag{1}$$

where R is the radius of the Earth. (This formula is valid for $d \ll R$.) The formula expressing the interaction mfp., λ, in terms of the cross section (valid to a good approximation for *small* cross sections [7]) is:

$$\lambda \approx \frac{1670}{\sigma}, \tag{2}$$

where σ is measured in millibarns and λ in $\mathrm{g/cm}^2$. Thus, in the range of zenith angles, $0 \lesssim \zeta \lesssim \pi/2$, the mfp. varies between d and about $2 \times 10^7 \mathrm{g/cm}^2$. Correspondingly, if the cross section of the process to be observed satisfies the approximate inequality,

$$7 \times 10^{-5}\mathrm{mb} \quad \lesssim \quad \sigma \quad \lesssim \quad 4 \times 10^{-3}\mathrm{mb},$$

the first interaction, on the average, takes place in or near the neutrino telescope. Smaller cross sections — all the way down to the Standard Model weak interaction cross section — can be explored in a similar way. However, the estimate of the mfp. quoted above is no longer reliable, since the amount of matter between the detector and the incident beam depends strongly on the geology of the environment of the telescope.

Due to the fact that the initial interaction takes place in or near the detector, the produced hadrons initiate a mixed, hadronic – electromagnetic cascade right around the detector. Due to the high density and low average nuclear charge ($Z_{eff} \approx 3.3$) of the environment in which the cascade evolves, such water showers have some peculiar features both with respect to cascades developing in air and in absorbers like Pb. (For all practical purposes, one can take $\rho \approx 1$ even at a depth of 4 km due to the low compressibility of water.)

We now turn to estimating some important characteristics of these showers in order to be able to recognize them in a neutrino telescope.

Let us notice the following qualitative features of a water shower.

- The shower is nucleon poor. In fact, baryon pair production is rare in any hadronic interaction; moreover, due to the low effective atomic number of the environment, ($A_{eff} = 6$) the probability of knocking out a substantial number of the target nucleons in any given interaction is small.

- With the exception of particles containing c, b and t quarks produced in any of the interactions, charged particles interact rather than decay at all energies of interest. In fact, for charged pions (the most copiously produced charged hadrons), the interction mfp. is about 78 g/cm^2, see *e.g.* [8], whereas the decay length in water is $\approx 800E/m_\pi$ g/cm^2. Neutral pions still decay at most energies of interest: with a decay length, $c\tau \approx 25$nm, the interaction and decay mfp. in water become roughly equal at $E_{\pi^0} \approx 4$PeV.

We calculate the cascade development making the following approximations.

1. We neglect the production of all particles except pions. We further assume that pions of all charges are produced at the same rate.

2. We completely neglect the decay of charged pions and the interaction of neutral ones.

3. We neglect photoproduction of pions.

4. We compute the cascade development in Approximation A both for the hadronic and electromagnetic components. (The cascade is computed in the diffusion approximation; lateral development is neglected. In the case of the hadronic component, processes like pion capture, nuclear breakup, *etc.* are neglected. Likewise, in the development of the electromagnetic component, Compton scattering and ionization are neglected.)

5. We assume that, apart from the initial interaction, the evolution of the cascade takes place according to the Standard Model. This is justified by the circumstance that — as described in the references quoted — the cross section of either process considered here is expected to rise rapidly around its characteristic energy and then go into saturation.

As discussed elsewhere, *cf.* [9], this approximation should be adequate for gaining an understanding of the main qualitative features of the cascade. Due to the fact that one's understanding of the initial interaction is very sketchy at best, a more accurate computation of a cascade without knowing the details of the process initiating it is not warranted.

With these premises, we now turn the computation. Due to the fact that photoproduction is neglected, the hadronic and electromagnetic parts of the cascade can be calculated in separate steps. The hadronic component evolves autonomously; neutral pion decay merely acts as a source for the electromagnetic component.

In order to compute the hadronic component, we write down the standard transport equation for a *single component cascade*, since there are only pions present. We have:

$$\frac{\partial H(E,x)}{\partial x} = -H(E,x) + \int_E^\infty \frac{dE'}{E} F\left(E,E'\right) H(E',x). \tag{3}$$

Here, x stands for the thickness of the absorber measured in units of the interaction mfp. and $H(E,x)$ is the differential distribution of the pions. The fragmentation function, F, is taken to be of the form:

$$F(E,E') = \Theta\left(E' - E_{crit}\right) f(z), \tag{4}$$

where z is a Feynman scaling variable, $z = E/E'$; the energy E_{crit} is the energy below which the produced pions have such a low energy that dissipative processes (nuclear breakup, *etc.*) begin to compete successfully with particle production. We found that taking $E_{crit} \approx 500$GeV (corresponding to $\sqrt{s} \approx 30$GeV) is an adequate choice.

The scaling function, $f(z)$, can be reasonably well approximated by an expression of the form:

$$f(z) = Cz^{-0.9}\left(1-z\right)^3 \Theta\left(z - z_{min}\right). \tag{5}$$

The parameters C and z_{min} are determined from the conditions of energy conservation and from the value of the charged particle multiplicity (assumed to be energy independent), *cf.* [9]. We found $C \approx 0.45$ and $z_{min} \approx 0.008$. Apart from the presence of a critical energy, E_{crit}, all violations of Feynman scaling are neglected.

In order to solve eq. (3), one uses a combination of analytical and numerical methods as described in [9]; this assures a much higher accuracy than the asymptotic methods (saddle point approximation, *etc.*) used before digital computers appeared. In essence, the method consists of generating an iterative solution to the transport equation. The resulting integrals are then evaluated numerically. The computational time rquired is a small fraction of what would be needed for a full scale Monte Carlo calculation. (As discussed before, any gain in accuracy by using a Monte Carlo simulation is a purely illusory one.)

The transport equation is solved with an initial condition representing the "new physics". Due to the theoretical uncertainties, we chose a very simple model of the energy distribution, *viz.* we distributed the primary energy equally among the secondaries emerging from the first interaction. In a different context, when the characteristics of the first interaction were known, it was checked that this

approximation is adequate if the required accuracy is not higher than about 50%, [7]; hence, it should be adequate here. We put for a fixed primary energy:

$$N(E,0) = N_0 \delta\left(E - E_0\right), \tag{6}$$

where E_0 and N_0 are the primary energy and initial multiplicity.

One cannot find simple analytic expressions for the solution of eq. (3). In Figures 1 and 2 we display the integral distribution of charged hadrons,

$$N_(> E, x) = \int_E^{E_0} dE' N(E', x)$$

for $E = 10$Gev and $E = 100$GeV, respectively; the primary energy and initial multiplicity chosen were $E_0 = 10$PeV and $N_0 = 20$. (The value chosen for the initial multiplicity is not critical, since the solution depends linearly on it.)

One notices that — as expected — the integral distribution for a lower E is broader in x than the one for a high energy. In essence, this is a consequence of energy conservation: particles of lower energy occur further downstream than ones of high energy.

The transport equation for the electromagnetic component $(e^{\pm}, \gamma)$ is handled in a similar fashion. Apart from the very beginning of an electromagnetic cascade, the number of electrons, positrons and photons are almost equal to each other at the relevant energies. Consequently, they can be adequately described by a transport equation of the form,

$$\frac{\partial \Gamma(E, x_R)}{\partial x_R} = -\Gamma(E, x_R) + \int_E^{\infty} \frac{dE'}{E} \phi\left(\frac{E}{E'}\right) \Gamma(E', x_R) + S(E, x_R). \tag{7}$$

In the last equation, x_R stands for the absorber thickness measured in units of the radiation length and Γ stands for the distribution of photons; as asserted, at all distances but the very smallest ones, one can take the distributions of the photons and charged leptons to be the same. The function ϕ is the fragmentation function in the traditional Heitler–Jánossy approximation, *cf.* [10]. (The fact that putting $\phi(E, E') \approx \delta(E - E'/2)$ is an acceptable approximation explains, in essence, why the electron and photon distributions are about the same.) Finally, $S(E, x_R)$ is the source of the electromagnetic component. To a fair approximation,

$$S\left(E, x_R\right) = H\left(2E, x_R\right).$$

This is due to the fact that photons almost exclusively arise from the decay of neutral pions; furthermore, at high energies, the photons share the energy of the decaying π^0 equally, and, finally, the number of photons from π^0 decay is, to a good approximation, equal to the number of charged pions.

The solution of the transport equation eq. (7) can be obtained in the same way as described in connection with the transport equation for hadrons. In Fig. 3 we display the integral distribution of the electromagnetic component for the same

initial conditions as used in computing the hadron distribution. For the ease of comparison, the hadronic and electromagnetic components are plotted using the same unit of length (meters), assuming a constant density, $\rho \approx 1$.

The distributions shown in Figures 1 through 3 are *typical*: variations in the primary energy by factors of about 100 change the total number of particles, but they, in essence, leave the profiles of both the hadronic and leptonic components unchanged.

One concludes that events of the type described above are characterized by a large amount of energy released around the detector within a rather small volume. The characteristic longitudinal distances are about 10 meters or less and, due to the high energies involved, the transverse size is considerably smaller. The energy released in this volume is close to the energy of the incident neutrino. We believe that such a signature is practically free of background. However, this question cannot be answered without detailed and detector dependent simulations.

Some potential sources of background one can think of are:

- Normal neutrino interactions occurring close to the detector, arising from neutrinos incident at a large zenith angle ($\zeta \approx \pi/2$, say, due to fluctuations in the occurrence of the first interaction.

- One half of the Learned–Pakvasa process [13], *i.e.* either the production or the decay of a τ occurring near the detector, the other half being sufficiently far away so as to escape detection.

- Muons of energies in the 10 PeV range (or larger) passing through the detector. Such muons lose energy at the rate of about 0.5 TeV/m and thus, they may deposit a substantial amount of energy in the detector within a short distance.

While a quantitative answer requires a detailed study of the characteristics of each type of event mentioned above and a careful simulation of their appearance, one is under the impression that the signal we described here stands out by the large *energy density* deposited in the detector.

One should also study in more detail the possibility of distinguishing between the events generated by "composite neutrinos" (see [3]) and multiple gauge boson production. At this point we can make a few qualitative conjectures only. In the case of the multiple production of gauge bosons, about 70% of the W/Z bosons decays hadronically, and the remainder decays into e, μ, τ, with a branching ratio of about 10% each. Thus, in such an event, the electromagnetic component of the cascade starts early, it being fed initially by the prompt electrons coming from the decay of the gauge bosons. It is not clear at this point whether such an effect can be observed in the presence of the large hadronic component. Probably, one has a better chance of observing the muons emerging from the decay as it was pointed out by Ringwald, [6].

By contrast, the "composite neutrino" scenario will, probably, lead to a smaller multiplicity of muons (probably, just one hard muon at the vertex where the neutrino breaks up into its "preons" [11]). Hence, the observable to be watched in this respect is the number and energy distribution of prompt muons.

In a recent publication [12], the KAMIOKANDE collaboration described a somewhat unusual occurrence. Apparently, a particle penetrated about 3 km of rock[2] corresponding to an absorber depth of perhaps 10^6g/cm^2 after which it interacted in the neighborhood of the detector. As a result of the interaction, a large amount of energy was deposited in the detector: a substantial number of PMTs having been saturated. Unless the event is due to a very rare fluctuation, the interaction cross section of the primary was about 10^{-3}mb or so. It is amusing to speculate that thereby the first event of the type described in this letter may have been observed.

Acknowledgement

This research has been supported in part by the U.S. Department of Energy under Grant # DE–FG–02–85ER40211.

This work was completed during the authors' visit at the University of Florence, Summer 1994. We thank Roberto Casalbuoni for the hospitality extended to us and the National Institute for Nuclear Physics (INFN) for partial financial support.

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Figure Captions

Fig. 1 Integral spectrum of hadrons of energy $E > 10$GeV. The primary energy of the first interaction is assumed to be $E_0 = 10^7$GeV, initial multiplicity, $N_0 = 20$. The hadronic cascade shown is the one generated by an "average hadron" emerging from the first interaction.

Fig. 2 Same as Fig.1, for hadrons of energy $E > 100$GeV.

Fig. 3 The electromagnetic component of the shower generated by an "average hadron" emerging from the first interaction; leptons $(\mathrm{e}, \bar{\mathrm{e}}, \gamma)$ with energy, $E > 10$GeV. For comparison, the hadronic component is plotted by a dotted line.